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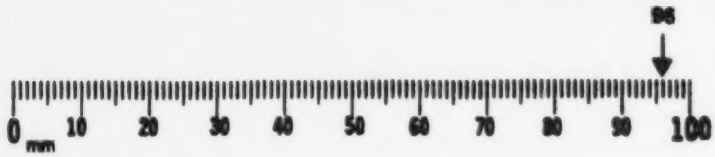

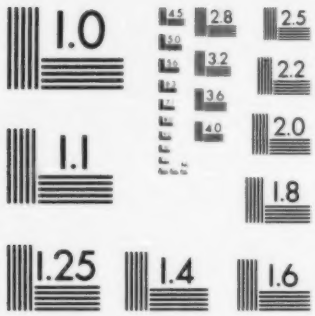

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Subject **NEW EQUIPMENT FOR HOLOGRAPHY IN THE FIELD**

The attached Research Report No 87-250-K shows that holography can be made to work in the field environment, thus opening up nondestructive testing and stress detection to holographic assessment.

The technique is no longer confined to a vibration isolation table. The report describes a preliminary experiment in which holographic fringe patterns due to static deformation were obtained on objects which were situated on ordinary tables or on the floor. This work is a "first" combining computer vision with pulsed lasers and instant holographic cameras.

Further work specified in the report would develop the technique to make it useful for routine tests.

We solict your comments on the report and your input on future work and further applications.

A.F. Baljet
Manager
Electrical Research Department
(Ext 6513)

D.L. Mader
(Ext 6084)

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To: Dr. D. Mills
Director of Research

TOWARDS FIELD HOLOGRAPHY

David L. Mader

The structural integrity of pressure vessels and pipes could now be assessed by holography in the field environment with further development of the prototype equipment described in this report. Previously, we made holographic interferograms of pressurized components on a vibration isolation table with a cw laser. Now, interferograms have been obtained without use of vibration isolation using pulsed ruby and YAG lasers to freeze motion. Instead of hologram viewing with a separate cw laser, the pulsed laser itself was used with a video camera and frame grabber to capture the image and hold it between viewing pulses. Techniques to overcome unwanted motion of the test piece are described, so that fringes due to deformation alone can be seen.

INTRODUCTION

Holographic interferometry provides a sensitive non-contact optical method to obtain strain and displacement of objects when they are subjected to a mechanical load or thermal expansion. What is obtained is an interferogram in which the object under test is seen covered by fringes that indicate contours of equal displacement. The technique is sensitive, since each fringe represents a movement of half of a wavelength of the laser light being employed.

Proposals to enter into holographic research at Ontario Hydro were made by Harvey/1/ and Boggs/2/. Expertise in holographic interferometry and speckle interferometry has been developed at Ontario Hydro in a number of projects/3-20/ reviewed in part in Appendix I.

job	file	date	report no.
16-660-050	819.36	November 24, 1987	87-250-K

Holography is used routinely in industrial NDT (nondestructive testing) of aircraft tires and aircraft honeycomb panels. One possible NDT use at Ontario Hydro could be boiler tube inspection in thermal plants. Another application in both thermal and nuclear plants could be identification of high stress regions in the pressure boundary as a screening test for ultrasonic flaw detection/14/.

The use of pulsed lasers for ordinary holography, rather than holographic interferometry, under field conditions in nuclear power plants is described by Tozer et al/21/. Measurements on these images could detect bulges down to 0.2 mm.

In the laboratory work at Ontario Hydro useful results have been obtained as follows. In studies of deformation it was shown that a repair procedure employing an ice blocking technique did not cause permanent deformation of heat transport tubes/6/. Similarly it was shown that garter spring repositioning with magnetic impulses used in LSFCR (SLAR) work did not produce permanent deformation/7/. In support for a second spacer relocation concept with mechanical vibration, a vibration visualization experiment was able to show the modal pattern produced by a pair of vibrators inside the pressure tube. A measurement on hydride blister strain in a pressure tube sample was obtained with speckle interferometry, a laser technique related to holography/20/. Turning from generation to distribution, holographic studies have furthered knowledge of the mechanisms responsible for insulation degradation by water treeing in underground cables/17/. Future laboratory work may touch on two-phase flow, fracture mechanics, and leak-before-break tests.

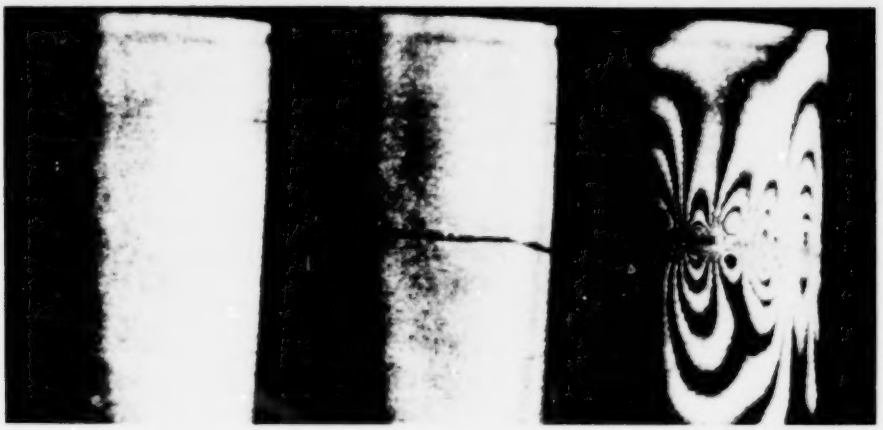
This report describes progress towards holographic NDT in the field with static loads such as thermal expansion or pressurization.

RESULTS FROM FIELD SIMULATIONS

To simulate the vibration environment that would be encountered in field holography, experiments were done with the apparatus situated on ordinary tables rather than vibration isolation tables as described in Appendix II.

Fig 1 shows a holographic interferogram of a Coke can loaded with a rubber band obtained without vibration isolation through use of a pulsed YAG laser. A sandwich hologram was made consisting of a pair of holograms, one taken in the initial state and one taken after loading. The holograms were made on glass photographic plates with silver halide emulsions. The video system indicated in Fig 3 was used to view the pair of holograms with the laser pulsing five times per second. Initially a fringe pattern was visible which showed the effect of deformation from the rubber band combined with a small amount of movement. Then the hologram

plateholder was tilted so as to remove the unwanted fringes due to motion, as described more fully in Appendix III.



(a) Initial (b) Loaded (c) Interferogram

Fig 1. Pulsed laser obtained strain pattern on Coke can loaded with rubber band without need for vibration isolation. Sandwich hologram allowed removal of unwanted fringes due to movement.

In real-time interferometry the fringe pattern is updated continuously so that the effect of changing the load can be seen. Only one hologram is made, the same as the first hologram of the initial state in sandwich holography. Then the light forming the image from the hologram is made to interfere with the light reflected directly from the object itself to create the interferogram. As the load changes, the interferogram changes in response, with an update rate equal to the laser pulse rate. The example in Fig 2 shows the door of a cabinet standing on the floor behind the table bearing the hologram. The door was heated by touching it at one spot, causing the pattern of curved fringes showing uneven thermal expansion.

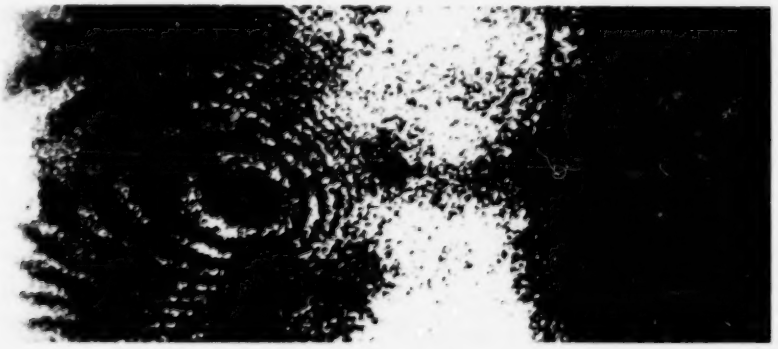


Fig 2. Real-time interferogram of thermal expansion of cabinet.

PROPOSAL FOR FIELD HOLOCAMERA

A proposed apparatus for field holography is shown in Fig 3, which incorporates a pulsed laser and means for motion compensation discussed in Appendix III and Appendix IV. Figure 3 incorporates more or less standard elements from three disciplines: pulsed holography, sandwich holography, and computer vision. Development of the apparatus would include a survey of vendors for a suitable small pulsed laser, and packaging the system for field use.

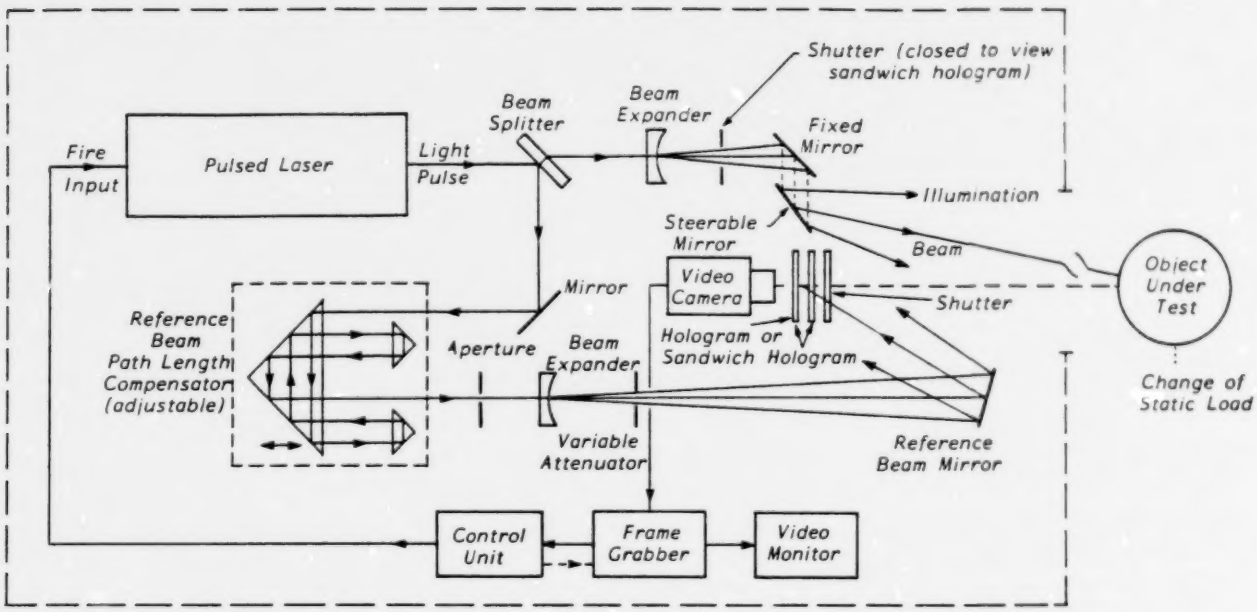


Fig 3. Field holocamera with pulsed laser and video system. The holder for the hologram(s) is mounted on a tilt table for compensation of object motion. Hologram reconstruction (viewing) is done with the pulsed laser, not a separate cw laser. A computer vision system captures and holds the images between pulses.

In holography two beams of light are required: one to illuminate the object as in photography, and one as a reference beam to illuminate the hologram directly. These two beams are derived from the same laser by means of a beam splitter so that they are coherent. A second difference from photography is that there is no lens in front of the hologram and what is recorded is the wavefront of the light reflected from the object. Thus the process of viewing a developed hologram is usually known as wavefront reconstruction or hologram reconstruction in which the original reflected wavefront is reproduced for viewing.

In Fig 3 the light pulse from the pulsed laser is shown falling on a glass plate serving as a beam splitter. The transmitted

beam passes through a concave lens which spreads it out into a cone of light which then is reflected from two mirrors and is used to illuminate the object. The beam reflected from the beam splitter is directed by a mirror into a reference beam pathlength compensator consisting of three right angle retroreflector prisms. To accommodate variable object distances one of the prisms is adjustable so that the distance travelled by the reference beam from the beam splitter to the hologram is equal to that travelled by the other beam from the beam splitter to the object and back to the hologram. Before making a hologram the variable attenuator in the reference beam path is adjusted to make it approximately two (for silver halide) to ten (for thermoplastic) times as intense as the light from the object.

After the hologram is exposed and developed it is viewed on the video monitor in Fig 3 by closing a shutter in the illumination beam path and firing the laser in synchronization with the video camera under the control of a control unit which was a personal computer/18/ in the experiments described above. The frame grabber stores the image from the hologram until the next laser pulse is fired. With this system the hologram is reconstructed with the same wavelength and the same reference beam as was used for exposure so that the reconstructed image is an exact replica of the object seen in its original location. (Exact replication is what makes real-time interferometry possible.)

For sandwich holography two holograms are made for the initial and final loading states and are viewed simultaneously with the illumination shutter closed. These two holograms are to be held in the same hologram holder which is to be mounted on a tilt table. With the laser pulsing, the interferogram would be viewed on the video monitor and the tilt table would be adjusted to remove unwanted fringes due to any overall movement of the object which may have occurred due to application of the load.

For real-time interferometry, one hologram is made of the object in its initial state and is then viewed while the illumination shutter is open so that the video camera sees both the image from the hologram and the object itself. The interferogram is viewed on the video monitor and the variable attenuator is adjusted for the best fringe contrast. Fringes due to overall movement of the object may be removed leaving just deformation fringes by tilting the steerable illumination mirror or by tilting the hologram.

FUTURE DEVELOPMENT NEEDS

A. Create nondestructive testing data base. Do holograms on field specimens in the cw lab. The work consists of sample preparation, holography, fringe pattern analysis, and record keeping.

B. Develop pulsed system for field use. The concept shown in Fig 3 would be developed by acquiring compact components and packaging for field use.

C. Develop holography for mechanical and metallurgical research. Holography can be used to monitor crack progress in fracture mechanics and in leak-before-break tests. With pulsed lasers, holograms can be obtained of sprays for droplet counting and sizing. Time average holograms clearly show resonant vibration modes.

D. Research techniques for compensation for large movement. Any large movement of an object that may occur during application of a test stimulus could be handled by tracking its motion and moving the holographic apparatus in compensation.

CONCLUSIONS

Progress has been made towards implementation of holographic interferometry with static test loads in the field environment, with application to nondestructive testing, and strain visualization and measurement. Previously, we made holograms on a vibration isolation table with a cw laser. Now, interferograms have been obtained without use of vibration isolation using pulsed ruby and YAG lasers to freeze motion. Instead of hologram viewing with a separate cw laser, the pulsed laser itself was used with a video camera and frame grabber to capture the image and hold it between viewing pulses. Techniques to overcome unwanted motion of the test piece are described, so that fringes due to deformation alone can be seen. Plans are given for a holography camera to obtain interferograms of mechanical components tested with static loads under field conditions.

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Electrical Research Dept

Submitted:

D L Mader

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Science Section

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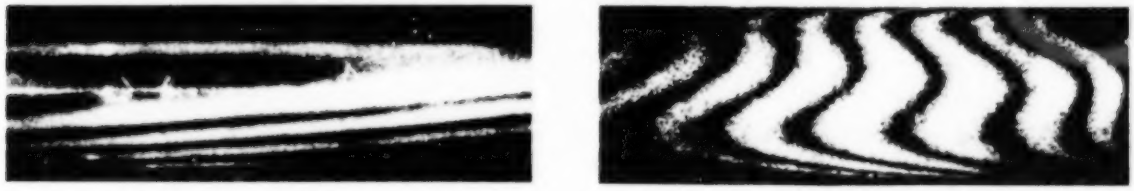
APPENDIX I. BACKGROUND EXPERIMENTS WITH CW LASER

Holographic interferometry responds to the displacement of the surface of a mechanical component, leading to a technique for visualization and measurement of static displacement, vibration, thermal expansion, deformation, and strain. This technique has been applied to vibration mode visualization, measurement of thermal expansion coefficients, and nondestructive testing.

Vibration modes were observed on a turbine blade. A high frequency resonant mode is shown in Fig 4 on the trailing edge where the blade is susceptible to failure.

Fig 4. Vibration resonance on turbine blade seen with time average hologram.

A holographic study in support of coal-fired power plants was able to show that degraded boiler tubes could be distinguished from new ones/9/. These tubes are exposed to flame and fly ash, leading to erosion and consequent wall thinning.



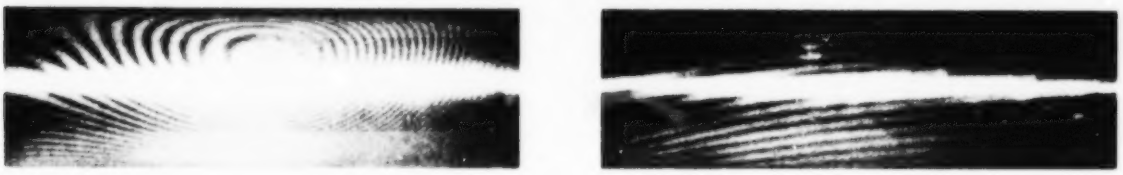
(a) New tube (b) Eroded tube

Fig 5. Holography could find eroded tubes in coal-fired boilers.

Double exposure holographic interferograms were taken on both new and eroded boiler tube samples subjected to pressure. Rust and scale on the eroded tube were of no hindrance in taking the holograms; in fact the diffuse surface avoided glint and highlights. Fringes approximating the elliptical shape expected theoretically/5,12,13,16/ for an ideal tube were obtained on a sample of new tubing shown in Fig 5(a). By contrast, an eroded

sample cut from a section of tubing that had failed in service gave the pattern seen in Fig 5(b) where the fringes depart considerably from elliptical. In this sample the wall was thinned from 10 mm to 9 mm over 30% of the circumference, approximately.

In CANDU reactors a concern arose that the use of magnetic pulses to reposition the spacers between pressure tubes and their surounding calandria tubes could damage the pressure tubes. In a holography test/7/, a sample of pressure tube was mounted on a two-part repositioning jig. A hologram was made in a holography lab and then the sample was taken to an electromagnetics lab where a coil was inserted and a current pulse of 136 kA was administered from a capacitor bank charged to 5.5 kV. Finally, the sample was returned to its original position on the optical table using the repositioning jig for real-time interferometry with the results seen in Fig 6.



(a) Thermal expansion (b) No permanent deformation

Fig 6. No deformation of pressure tube due to magnetic pulsing.

Shortly after the pulse was fired the tube felt warm and the thermal deformation in (a) was seen. After returning to room temperature the fringe pattern seen in (b) indicated little, if any, deformation. The pattern of straight fringes is due to a slight misalignment in the jig, which causes inadvertent motion.

Turning to NDT experiments, an artificial flaw was cut into the inside wall of a water pipe to probe the ability of holography to monitor an interior crack/4/. A double exposure hologram with a moderate pressure change gave the fringe pattern seen in Fig 7 where the flaw is clearly identified. Fringe patterns such as this could help to visualize and measure performance of a pipe sample in a leak-before-break test.

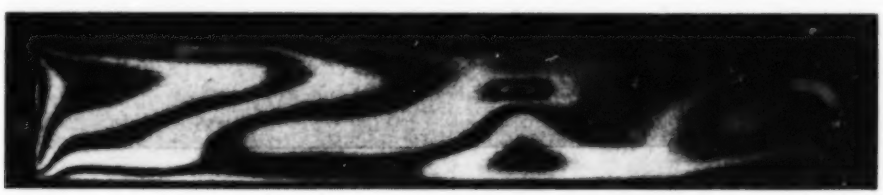


Fig 7. Interior crack detected by exterior fringe pattern.

APPENDIX II. PULSED HOLOGRAPHY EXPERIMENTS

Experiments were done to explore the "sandwich hologram" technique of Abramson/23/ for obtaining interferograms which provide a capability for fringe manipulation, to remove fringes due to unwanted motion of the object. This capability is not provided by double exposure holograms, which have frozen-in fringes.

Sandwich holograms were made with two pulsed lasers: a ruby laser at Ryerson Polytechnical Institute, and a YAG laser at Ontario Hydro. In both cases, interferograms were obtained and fringe manipulation was found to be possible. The Ryerson experiment showed that a pulsed ruby laser can be used to make sandwich holograms on silver halide plates, and that a HeNe laser can be used for reconstruction provided the angle of incidence appropriate to the HeNe wavelength is used. Fig 1 shows an interferogram on a Coke can, loaded with a rubber band around its middle, obtained without vibration isolation through use of the YAG laser and a sandwich hologram. A video system was used to view the interferogram with the laser pulsing at 5 Hz. Initially a fringe pattern was visible; this pattern indicated that a small amount of movement had occured. It was found that the hologram plateholder could be tilted so as to remove the unwanted motion fringes.

An experiment on the real-time technique was done with a frequency doubled YAG laser and an instant holocamera that uses photoconductive thermoplastic plates. These plates are not processed with photographic chemicals; instead they are sensitized with electrostatic charge and are developed in the holocamera itself in 10 seconds by heating. The holograms so produced are brighter than those formed on silver halide plates, and so are better for the real time technique since the light from the holographic image is comparable in brightness to that from the object, a condition for a good interferogram.

An interferogram captured by the computer vision system is given in Fig 8 for part of a cabinet door. The fringes were seen to vary from pulse to pulse as the response of the door to ambient vibration was caught at various points during the vibration cycle.

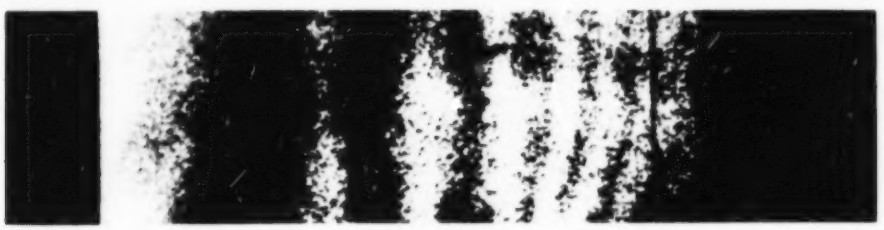


Fig 8. Vibration of cabinet standing on floor.

APPENDIX III. DESIGN CONSIDERATIONS FOR FIELD HOLOGRAPHY

Choice of laser. Continuous (cw) lasers are a convenient source of coherent light for holography, though their use is, generally speaking, confined to a vibration isolated environment. The reason for this is that the entire apparatus must remain stable to better than one wavelength of light throughout the entire time the hologram is being exposed. With a cw laser the hologram may require an exposure time from a fraction of a second to minutes. However, even in the presence of vibration, the above stability requirement can be met if the exposure time is short enough. Thus, pulsed lasers with pulse durations of 10 to 100 ns may be used to make holograms in essentially any vibration environment. Pulsed laser choices for holography are ruby lasers and YAG lasers. Frequency doubling crystals are available for YAG lasers which give them a visible green output rather than their basic infrared output.

The customary practice in pulsed holography is to use a pulsed ruby laser (wavelength 694 nm) to make the holograms and a continuous HeNe laser (wavelength 633 nm) to view (reconstruct) them. Considering the distortion arising from reconstruction with a different wavelength from that used to make the hologram, Vest suggested the use of Nd:YAG lasers so that the same laser could be used for both functions/22/. Alternatively, work on holography for nuclear power plants done in the U.K. at Marchwood Labs for the Central Electricity Generating Board used three lasers: a pulsed ruby laser to make the holograms, with a cw argon ion laser driving a dye laser at the ruby wavelength (694 nm) to view the holograms/21/.

For capturing small displacements with holographic interferograms, double pulse lasers are available commercially which provide two separate laser pulses during one flashlamp pulse. The two laser pulses can be separated in time by as long as a millisecond. A single hologram is made and is double exposed by the two pulses. Such holograms are limited in usefulness to capturing small displacements occurring over a period of a microsecond to a millisecond and as such can be used for high frequency vibration detection, or for defect detection at a specific location through application of a timed impulse load.

Experience with the lasers used for the experiments described in Appendix II was as follows. The Ryerson laser was a 1 Joule pulsed ruby laser made by J-K Lasers and sold by Lumonics. Holograms originally made with this laser (without diffusers for interferometry) exhibited spurious fringes due to mode hopping. These fringes disappeared after the laser was specially tuned by Lumonics for holographic interferometry. The beam was spread out into a cone of light by means of reflection from a convex mirror. At the site of the table with the apparatus mentioned above the beam had spread out to a spot over a metre wide, showing that

holograms could have been obtained of objects considerably larger than the Coke can used in the experiment.

The maximum rate of firing pulses with the ruby laser is limited by heating effects in the ruby rod to about once every 15 seconds, though there is an option for pulses of reduced energy once every second. Thus, in the tradeoff between pulse energy and pulsing rate, the ruby laser affords giant pulses but at a low pulse rate.

The YAG laser at Ontario Hydro was made by Quantel to pump a dye laser. Instead of a ruby rod, it uses a Nd:YAG rod consisting of Ytterium Aluminium Garnet doped with Neodimium. These lasers permit a faster pulse rate than ruby lasers, with lower energy pulses of about half a Joule in this case. With the inclusion of a line narrowing etalon and a pinhole in the oscillator cavity this particular laser became marginally suitable for holography. New YAG lasers coming on the market are more suitable.

The YAG laser was more convenient than the ruby laser for set-up. A frequency doubling crystal was used to reduce the wavelength from the basic invisible YAG wavelength of 1.05 micrometers to the visible green wavelength of 503 nanometers. With the laser pulsing at 5 Hz one could adjust mirrors and beam blockers more or less in real time. Similarly, the higher pulse rate was able to provide nearly real time hologram viewing via a computer vision system. A further advantage was the fact that the doubled wavelength of green light was suitable for use with an instant holocamera, whereas this camera is essentially insensitive to the ruby wavelength with the presently available plates.

Compensation for movement. To obtain the interferograms shown in Appendix I under field conditions, the method must be able to accommodate static loads, which will usually induce unwanted movement of the component under test. For instance, when a pipe attached by an elbow is pressurized, the Bourdon effect will move the pipe. Therefore methods are needed to remove the effects of overall motion (rigid body motion or gross motion) of the component under test.

First, a double plate technique is described for use in conjunction with a single-pulse laser. Two separate holograms would be made of the component under test: one before the static load is applied, and one after. The images would be brought into registration in a coarse positioning operation, and then fine positioning would be done to achieve good fringe visibility and proper fringe shape. In a straightforward implementation of this idea, one hologram would be left stationary and the other one would be moved slightly to obtain registration. This implementation requires positioning accuracies better than a micrometer.

Second, Abramson's/23/ "sandwich technique" provides a less critical method for image registration. A hologram holder is used which can hold the two separate holograms, one in front of the other. The two holograms are exposed one at a time, are developed, and are returned to their original locations in the holder. The plate holder itself is mounted on a tilt table which allows the pair of holograms (the sandwich) to be oriented at will with respect to the reference beam during reconstruction. Both images move when the reference beam angle changes, but one moves slightly more than the other because of the slight separation between them. Thus the process of obtaining image registration can be done with coarse adjustments of the tilt table.

Sandwich holograms could be made more rapidly with an instant holocamera adapted for two holograms.

Third, a method of fringe control for real-time interferometry is given by Sciammarella et al/24/, who give a procedure to compensate for object movement through the use of tilt of the illumination mirror and give formulas from which the required horizontal and vertical mirror tilts may be calculated. An experiment on this method is described in Appendix IV.

Finally, it is suggested that the same result as that obtained by Sciammarella et al through tilt of the illumination mirror could also be obtained through tilt of the hologram. Then, a hologram tilting mechanism would work for real-time interferometry as well as for Abramson's method of fringe control with sandwich holograms.

Extraneous fringes. Interferograms respond to vibration of the object and to heat waves in the air. When these sources of disturbance are severe they can introduce extraneous fringes and when present to a lesser extent they can distort the fringe pattern.

Reciprocity failure. Photosensors can become less sensitive to light at very long or very short exposure times, the so-called reciprocity failure effect in photography. On silver halide holographic plates and on ordinary photographic film the effect was apparent with the 10 ns pulses from the YAG laser. By contrast, the CCD video camera and the photoconductive thermoplastic instant holocamera appeared to have their usual sensitivity. It should be noted that the pulse duration may not be extended with the YAG laser if frequency doubling to green light is desired, because the doubling crystal only works with high intensity which requires short pulse duration.

APPENDIX IV. MOTION COMPENSATION IN REAL-TIME INTERFEROMETRY

In real-time interferometry with a pulsed laser the fringe pattern is updated each time the laser is fired so that the effect of changing the load can be seen. Only one hologram is made, the same as the first hologram of the initial loading state in sandwich holography. Then the light forming the image from the hologram is made to interfere with the light reflected directly from the object itself to create the interferogram. As the load changes, the interferogram changes in response, with an update rate equal to the laser pulse rate.

As the load is applied, movement may obscure the deformation. Compensation for such motion may be obtained/24/ through tilt of the illumination mirror seen in Fig 3, or through tilt of the hologram holder as suggested in Appendix III. To explore the range of motion compensation, an experiment was done under controlled conditions with a cw laser and a vibration isolation table. A hologram was made of a Coke can mounted on a translation stage. A rubber band was placed around the middle of the can to provide a deformation fringe pattern. Then the stage was adjusted to introduce motion fringes into the real-time interferogram. The illumination mirror was then tilted to remove the motion fringes and recover the deformation fringes alone. In the limit of applicability of this compensation method, the fringe visibility goes to zero due to speckle decorrelation/24/. Backing off 40% from the limit, the results shown in Fig 9 were obtained.

(a) (b) (c)

Fig 9. Illumination tilt for motion compensation in real-time holographic interferometry. (a) Deformation alone. (b) Motion = 0.1 mm. (c) Compensated by tilting illumination mirror.